Automated Sensor Networks to Advance Ocean Science

Oceanography is evolving from a ship-based expeditionary science to a distributed, observatory-based approach in which scientists continuously interact with instruments in the field. These new capabilities will facilitate the collection of long-term time series while also providing an interactive capability to conduct experiments using data streaming in real time.

The U.S. National Science Foundation has funded the Ocean Observatories Initiative (OOI), which over the next 5 years will deploy infrastructure to expand scientists' ability to remotely study the ocean. The OOI is deploying infrastructure that spans global, regional, and coastal scales. A global component will address planetary-scale problems using a new network of moored buoys linked to shore via satellite telecommunications. A regional cabled observatory will "wire" a single region in the northeastern Pacific Ocean with a high-speed optical and power grid. The coastal component will expand existing coastal observing assets in order to study the importance of high-frequency forcing on the coastal environments.

These components will be linked by a robust cyberinfrastructure (CI) that will integrate marine observatories into a coherent system-of-systems. This CI infrastructure will also provide a Web-based social network enabled by real-time visualization and access to numerical model information, to provide the foundation for adaptive sampling science. Thus, oceanographers will have access to automated machine-to-machine sensor networks that can be scalable to increase in size and incorporate new technology for decades to come. A case study of this CI in action shows how a community of ocean scientists and engineers located throughout the United States at 12 different institutions used the automated ocean observatory to address daily adaptive science priorities in real time.

Connectivity Between Observations and Models

During its 5-year construction period, the OOI is committed to engaging the ocean sciences community. To fulfill this goal, researchers are developing a useful CI by using a "spiral design strategy" so that the oceanography community can provide input throughout the construction phase.

An example of this strategy was conducted in fall 2009 when the OOI CI development team used an existing ocean-observing network in the Mid-Atlantic Bight waters (MAB, spanning offshore regions from Massachusetts to North Carolina) to test OOI CI software. The objectives of this CI test were to aggregate data from ships, autonomous underwater vehicles (AUVs), shore-based radars, and satellites and then make the aggregated information available in real time to five different data-assimilating ocean forecast models. Scientists use these multimodel forecasts to automate future underwater glider missions so that they can study quickly developing and fast changing characteristics of nearshore marine environments. Scientific interests spanned from the formation of the winter phytoplankton bloom to the role of storms that induce sediment resuspension from the seafloor. The test demonstrated the feasibility of two-way interactivity between the sensor web and predictive models.

Specifically, this effort tested the CI planning and prosecution software, which enables operators to monitor and control individual components within an ocean-observing network. The CI software coordinates and prioritizes the shared resources, allows for the semiautomated reconfiguration of asset tasking, and thus facilitates an autonomous execution of observation plans for both fixed and mobile observation platforms. For this effort, numerical model ocean forecasts, made interoperable by standard Web services, allowed scientists to simulate potential robot trajectories. This was used to guide scientists' decisions about whether desired target areas could be reached by autonomous vehicles.

For example, the software allows a scientist to determine if any available underwater glider could be redirected to map a surface plume of turbid water that had been identified in an ocean color image within a 24-hour period. The software then could determine the optimal path to map the turbid plume. Such efforts were coordinated through a Web portal that provided an access point for the observational data and model forecasts. Researchers could use the CI software in tandem with the Web data portal to assess the performance of individual numerical model results, or multimodel ensembles, through real-time comparisons with satellite, shore-based radar, and in situ robotic measurements.

Testing CI Outputs

To try out the CI's capabilities, scientists investigated the program's ability to remotely coordinate the mission of an array of AUVs that were acoustically networked. Scientists on shore in New Jersey used satellite data to define an operations area, which was forwarded to planners at the NASA/California Institute of Technology's Jet Propulsion Laboratory (Pasadena), who in turn e-mailed hourly AUV deployment instructions back to

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at-sea teams on boats off New Jersey. Each AUV was equipped with an acoustic modem that enabled underwater communications with other AUVs. A gateway buoy allowed real-time communication with science personnel on a ship. This system enabled AUV reports of status information such as position, speed, heading, and scientific sensor readings to be published on Google Earth™ and distributed to scientists around the United States in real time. These AUVs were outfitted with software that enabled them to access the available onboard data to autonomously adapt to the environmental features measured by scientific sensors.

Another test of the CI was to try to coordinate sampling between underwater gliders and the space-based Hyperion imager flying on the Earth Observing-1 (EO-1) (http://eo1.gsfc.nasa.gov) spacecraft. Hyperion images have a footprint of 7.5 × 100 kilometers, with a spatial resolution of 30 meters. This small spatial footprint makes it difficult to ensure that instruments closer to the ground are present for in situ verification measurements. The Hyperion swath can be adjusted to survey different regions, and therefore there is a possibility to mobilize in situ assets and simultaneously adjust the satellite sampling region to be coincident. During the field experiment, observational data and multimodel forecasts were analyzed to determine an optimal redirection for the satellite. These new coordinates were used by the EO-1 Web-based capability to change the spacecraft's surveying patterns (http://ase.jpl.nasa.gov). A 48-hour model forecast was then used by the CI software to colocate any gliders and plan their paths within the new EO-1 Hyperion swath. Two gliders were successfully moved to the swath; other gliders, which were not capable of reaching the swath, were diverted to accomplish other science missions.

Improving the Ease of Science

OOI's CI represents a major technology breakthrough in simultaneously coordinating satellite and underwater assets guided by multimodel forecasts. It provides a machine-to-machine interactive loop driven by a geographically distributed group of scientists.

As the number of ocean observatories increases globally, a sophisticated and scalable CI will be required. The OOI CI will provide functionality, allowing scientists to manage the complex networks while optimizing the science data being collected. The CI will also provide pathways to link other ocean networks, allowing more distributed groups to interact. The resulting global sensor net will be a new means to explore and study the world's oceans by providing scientists with real-time data that can be accessed via any wireless network.

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